Stellar Evolution at Low Metallicity: Mass Loss, Explosions, Cosmology
*ASP Conference Series, Vol. **VOLUME**, 2006*
Lamers, Langer, Nugis and Annuk

Evolution of Gamma-Ray Burst Progenitors at Low Metallicity

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Abstract. Despite the growing evidence that long Gamma-Ray Bursts (GRBs) are associated with deaths of Wolf-Rayet stars, the evolutionary path of massive stars to GRBs and the exact nature of GRB progenitors remained poorly known. However, recent massive star evolutionary models indicate that — for sufficiently low metallicity — initially very rapidly rotating stars can satisfy the conditions for collapsar formation. Even though magnetic torques are included in these models, a strong core spin-down is avoided through quasi-chemically homogeneous evolution induced by rotational mixing. Here, we explore for which initial mass and spin-range single stars of $Z = Z_{\odot}/20$ are expected to produce GRBs. We further find a dichotomy in the chemical structure of GRB progenitors, where lower initial masses end their lives with a massive helium envelope which still contains some amounts of hydrogen, while higher initial masses explode with C/O-dominated hydrogen-free atmospheres.

1. Introduction

Long gamma-ray bursts (GRBs) are believed to originate from rapidly rotating massive Wolf-Rayet stars (see Woosley & Heger 2004 for a review). Interestingly, recent observations indicate that GRBs occur preferentially in metal poor environments (Fynbo et al. 2003; Conselice et al. 2005; Gorosabel et al. 2005; Chen et al. 2005; Starling et al. 2005a). However, it has been questioned whether metal poor single stars are able to produce rapidly rotating WR stars as GRB progenitors, based on two reasons. First, stellar evolution models which include magnetic torques indicate that the core loses too much angular momentum during the giant phase to produce collapsar and GRBs (Heger, Woosley & Spruit 2005; Petrovic et al. 2005). Second, the lower the metallicity, the more difficult is the removal of the hydrogen envelope – without which jets from the central engine could not escape from the star – even from very massive stars (see, however, Meynet et al. 2005).

Two recent independent studies by Woosley & Heger (2005) and Yoon & Langer (2005) give a plausible solution to this problem. They considered so-called homogeneous evolution (Maeder 1987), where rotationally induced chemical mixing induces quasi-homogeneity of the chemical composition of the star throughout core hydrogen burning. In this case, single stars can become Wolf-Rayet stars without the need of stellar wind mass loss, and they avoid the giant phase that otherwise would cause a significant decrease of the core angular mo-

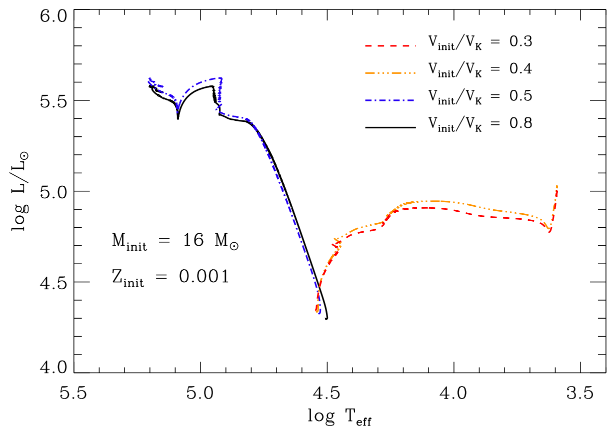

Figure 1. Evolution of 16 $M_\odot$ stellar models at $Z_{\rm init} = 0.001$, for different initial rotational velocities ($V_{\rm init}/V_{\rm Kepler} = 0.3, 0.4, 0.5, 0.8$), in the HR diagram.

mentum by magnetic torques. The above mentioned authors showed that such evolution can actually lead to the retention of enough angular momentum in the core to produce GRBs, if metallicity is sufficiently low ($Z \lesssim Z_\odot/10$). Here we present stellar evolution models at $Z = 0.001$ which include rotation and magnetic toques (Spruit 2002), and systematically investigate in which conditions stellar evolution can lead to GRBs, via such an evolutionary path.

2. Methods

The stellar models are calculated with a hydrodynamic stellar evolution code, which includes the effect of rotation on the stellar structure, rotationally induced chemical mixing, and the transport of angular momentum by magnetic torques (see Petrovic et al. 2005 and references therein). We follow Kudritzki et al. (1989) for stellar wind mass loss of hydrogen rich stars. Wolf-Rayet wind mass loss rates are adopted following Hamann et al. (1995), but reduced by a factor of 10, which corresponds to the recent estimates by Vink & de Koter (2005). The effect of the enrichment of CNO elements at the stellar surface on the WR wind mass loss rate is also considered such that, with a given surface condition, WC stars with $X_{\rm CNO} = 0.5$ and $X_{\rm He} = 0.5$ have about 10 times higher mass loss rates than WN stars. A metallicity dependence of $\dot{M} \propto Z^{0.69}$ and $\dot{M} \propto Z^{0.86}$ is adopted for hydrogen rich stars and WR stars, respectively, following Vink et al. (2001) and Vink & de Koter (2005). We do not consider overshooting in the convective region, but employ rather fast semi-convection with an efficiency parameter $\alpha_{\rm SEM} = 1.0$ (see Langer 1991). Uncertainties due to these assumptions, and their effects on the results are discussed in Yoon & Langer (2006).

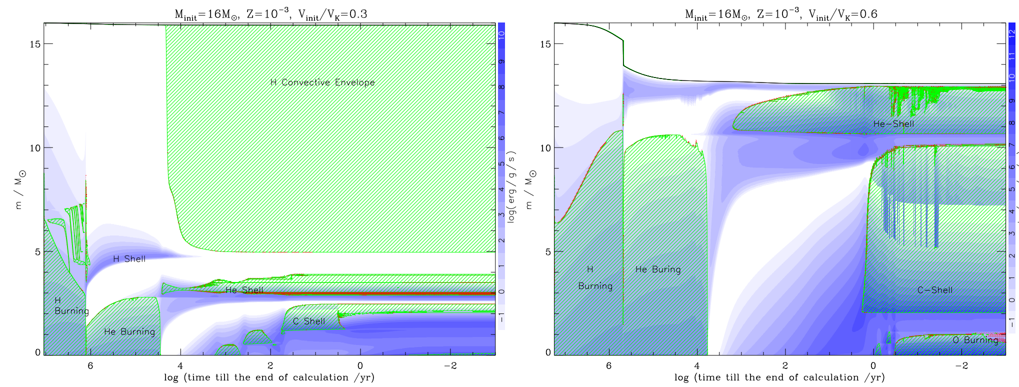

Figure 2. Evolution of the internal structure of the model sequences of $M_{\rm init} = 16 \mathrm{M}_\odot$ and $Z = 0.001$, with $V_{\rm init}/V_{\rm K} = 0.3$ (left panel) and $V_{\rm init}/V_{\rm K} = 0.5$ (right panel). Convective regions are hatched. Gray shading denotes nuclear energy generation.

3. Evolution of massive stars at $Z = 0.001$

As discussed by Maeder (1987), the evolution of rotating stars can bifurcate according to the initial spin rate. While non-rotating, or slowly rotating stars evolve redwards, rapidly rotating stars evolve bluewards due to very efficient rotationally induced chemical mixing. Figure 1 illustrates this bifurcation in the H-R diagram, with 16 $\mathrm{M}_\odot$ models. Initially slowly rotating stars ($V_{\rm init}/V_{\rm K} = 0.3$ & 0.4) transform into red giants with a massive extended hydrogen envelope (Fig. 2). The resulting CO core mass is about 2.8 $\mathrm{M}_\odot$, and the star is expected to explode as a Type II supernova leaving a neutron star as a remnant. On the other hand, the initially rapidly rotating stars ($V_{\rm init}/V_{\rm K} = 0.5$ & 0.8), which become WR stars on the main sequence due to rotationally induced mixing, have only a tiny compact hydrogen envelope during the core He burning phase (Fig. 2). Importantly, such a tiny envelope cannot spin down the rapidly rotating core, contrary to the case where stars evolve into red giants (Heger et al. 2005; Petrovic et al. 2005). Rather efficient angular momentum transport from the CO core occurs after the core He exhaustion, but the central core can retain enough angular momentum to produce collapsar (Woosley & Heger 2005; Yoon & Langer 2005). The CO core mass at the final stage is about 10.4 $\mathrm{M}_\odot$, which is large enough to form a black hole.

Not all stars which undergo quasi-homogeneous evolution end their life with a GRB. If the metallicity is too high ($Z \gtrsim Z_\odot/10$), mass loss results in a too strong spin-down of the star (Woosley & Heger 2005; Yoon & Langer 2005). At a given metallicity, homogeneously evolving stars of relatively low initial mass ($\sim 10\,M_\odot$) have a rather long CO core contraction time, and a rather massive He envelope after the He core exhaustion. In these stars, the CO core loses too much angular momentum by magnetic torques after core helium burning to produce a GRB. This imposes a lower initial mass limit ($M_{\rm min}$) for GRB formation. We find $M_{\rm min} \simeq 20\ \mathrm{M}_\odot$ with slow semi-convection ($\alpha_{\rm SEM} = 0.01$) as discussed in Yoon & Langer (2005), and $M_{\rm min} \simeq 12\ \mathrm{M}_\odot$ with fast semi-convection ($\alpha_{\rm SEM} = 1.0$), in agreement with Woosley & Heger (2005).

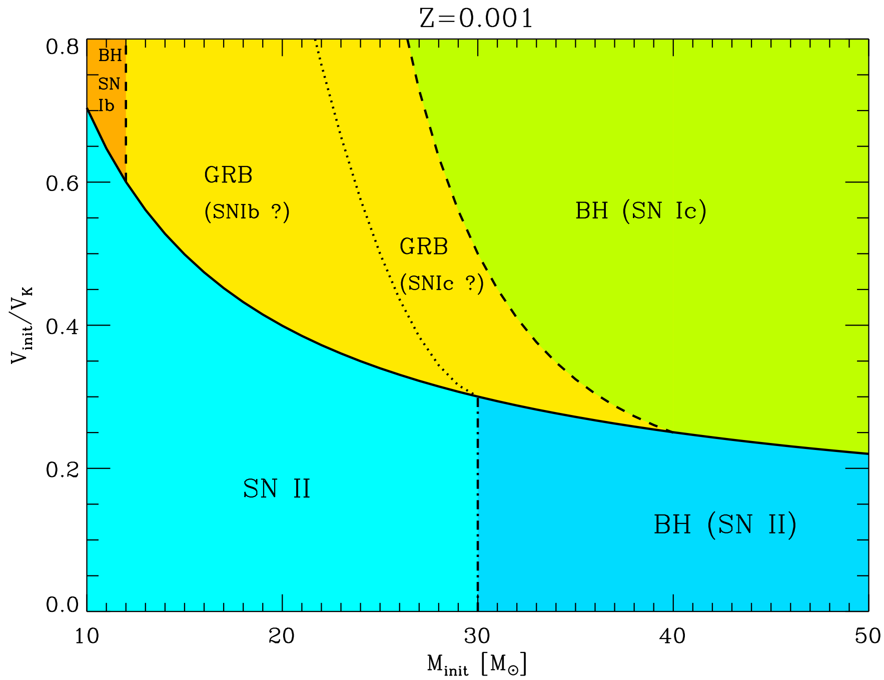

Figure 3. Final fate of rotating massive stars at $Z = 0.001$, in the plane of initial mass and initial fraction of the Keplerian value of the equatorial rotational velocity. The solid line divides the plane into two parts, where stars evolve quasi-chemically homogeneous above the line, while they evolve into the classical core-envelope structure below the line. Between the dashed lines is the region of quasi-homogeneous evolution where the core mass, core spin and stellar radius are compatible with the collapsar model for GRB production, while to both sides of it black holes are formed but the core spin is insufficient. This GRB production region is divided into two parts, where GRB progenitors do or do not possess a thick helium envelope (i.e. $\Delta M_{\rm He} \gtrsim 2.0\mathrm{M}_\odot$). The dashed-dotted line in the region of non-homogeneous evolution separates Type II supernovae (SN II; left) and black hole (BH; right) formation, where the minimum mass for BH formation is simply assumed to be 30 $\mathrm{M}_\odot$ (see, however, Heger et al. 2003 for a comprehensive discussion on the issue). From Yoon & Langer (2006).

The upper initial mass limit for GRB formation is imposed by different factors for different metallicities. At $Z = 0.001$, stars with $M_{\rm init} \gtrsim 40\ \mathrm{M}_\odot$ experience significant braking by rather strong mass loss, and cannot retain enough angular momentum in the core. Therefore, only those stars with $12\ \mathrm{M}_\odot \lesssim M_{\rm init} \lesssim 40\ \mathrm{M}_\odot$ are likely to produce GRBs, at $Z = 0.001$. This upper mass limit will decrease with increasing metallicity, due to stronger stellar wind mass loss. On the other hand, if the metallicity is very low ($Z \approx 10^{-5}$), the braking induced by mass loss is less important even for very massive stars. However, homogeneously evolving stars with $M_{\rm init} \gtrsim 60\ \mathrm{M}_\odot$ yields CO cores more massive than 40 $\mathrm{M}_\odot$ and likely undergo the pair-instability, preventing the formation of GRBs (Yoon & Langer 2005).

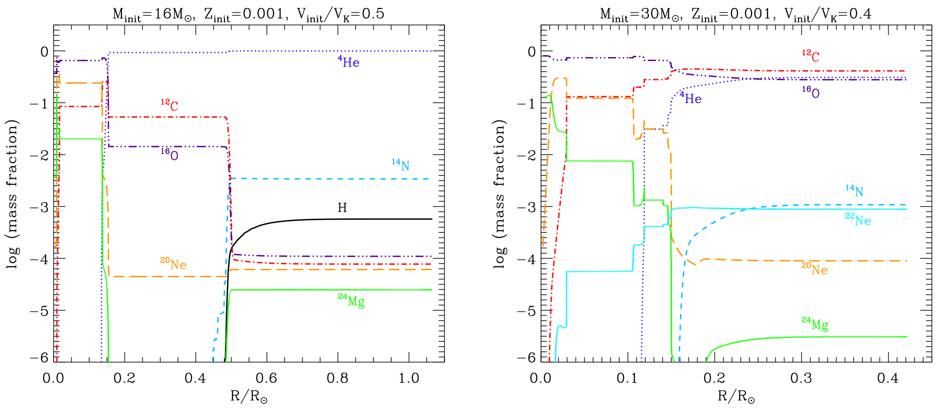

Figure 4. Chemical structure of two GRB progenitor models, as examples for the two different expected progenitor types. The left plot shows a "WN-type progenitor" ($M_{\rm init} = 16$ M$_\odot$, $V_{\rm init}/V_{\rm K} = 0.5$), with a final total mass of 13.07 M$_\odot$, a CO-core mass of 10.38 M$_\odot$, and hydrogen in its outer 0.2 M$_\odot$. The right plot shows a "WC-type progenitor" ($M_{\rm init} = 30$ M$_\odot$, $V_{\rm init}/V_{\rm K} = 0.4$), which ends up with 20.08 M$_\odot$ and a CO-core mass of 16.88 M$_\odot$.

In Fig. 3, we summarize the above discussion on the final fate of massive stars at $Z = 0.001$, in the mass-rotation plane, based on a grid of stellar models with different initial masses and spin rates (about 40 model sequences; Yoon & Langer 2006). Here, fast semi-convection ($\alpha_{\rm SEM} = 1.0$) is adopted.

4. Properties of GRB progenitors

Our models at $Z = 0.001$ predict two different types of GRB progenitors. Initially less massive stars give less massive CO cores and more massive He envelopes. As a result, stars with 12 M$_\odot \lesssim M_{\rm init} \lesssim 25$ M$_\odot$ end their life as WN stars with rather massive helium-rich envelopes ($\Delta M_{\rm He} \gtrsim 2.0$ M$_\odot$). Those might be characterized as Type Ib supernovae (Mazzali 2005, private communication; See Fig. 3). Remarkably, these stars also have hydrogen in their envelope (left panel in Fig. 4), which might be relevant to the high velocity HI absorption line observed in the afterglow of GRB 021004 (Starling et al. 2005b). On the other hand, more massive stars become WC stars in the end, which will explode as Type Ic supernovae (right panel of Fig. 4). Our models also predict that GRB progenitors of "WC-type" are more compact, more massive, and have envelopes which are more enriched with α-elements, than those of "WN-type" .

5. Discussion

The initial spin rate distribution of massive low-metallicity star is unknown, and thus our models can not readily predict a GRB formation rate at $Z = 0.001$. However, Langer & Norman (2006; see also the General Discussion after Session G, in this volume) argue that if the majority of GRBs were restricted to metallicities below $Z = Z_\odot/10$, about 5 percent of all massive stars with

such low metallicity should produce a GRB in order to obtain GRBs at a rate observed by BATSE. This requires that, at this and lower metallicity, more stars produce GRBs than stars are predicted to die as WR star due to stellar wind mass loss (cf. Meynet & Maeder 2005). Consequently, a significant low-metallicity bias in GRBs would — if confirmed — not only be consistent with the quasi-chemically homogeneous evolution scenario of GRB progenitors. It would require that indeed the evolution of low metallicity massive star differs significantly from that of massive stars in our Galaxy, in support of the scenario outlined above.

Acknowledgments. We are grateful to Alex de Koter, Paolo Mazzali, Philipp Podsiadlowski, and Ralph Wijers for fruitful discussions. SCY is supported by the Netherlands Organization for Scientific Research (NWO) through the VENI grant (639.041.406).

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